Rail4Future

Project title:	**Resilient Digital Railway Systems to enhance performance**
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Project number:	**882504**
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Deliverable D1.1.6

Simulation Deployment Results

Due date	
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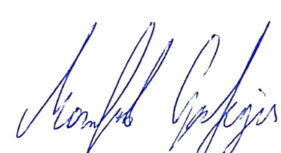
Submitted by	TU Wien MIVP

Version	Date	Edited by	Description
0.1	31.07.2024	Ozan Kugu	Creation
0.2	07.08.2024	Manfred Grafinger	Proof Reading
0.3	07.08.2024	Shiyang Zhou	Revision
0.4	06.09.2024	Alexander Meierhofer/ Stefan Reiterer	Addition
0.5	10.12.2024	Manfred Grafinger	Last changes, proof reading
0.6	27.01.2025	Ozan Kugu	Correction
1.0	27.01.2025	Manfred Grafinger	Finalzation

Deliverable released

by Area 1 Manager
Dr. Michaela Haberler-Weber

Deliverable released



by Area 1 Scientific Lead
Dr. Manfred Grafinger

1 Executive Summary

In this deliverable, we present and analyze simulation results derived from use case deployments within the R4F Platform. These results consist of validation curves (FMI-based vs. raw model simulation), CSV- and JSON-datasets, which are valuable for visualization, analysis and exchange among all stakeholders. This result acquisition has an important part in quality assurance of the use case implementation in the platform (see Deliverable D1.1.5 & D1.3.5). This process enables us to confirm the proper functionality of the integration, delivery, and deployment of assets associated with various railway use cases.

2 Table of Content

3 Abbreviations and Acronyms

Abbreviations / Acronyms	Description
AIT	Austrian Institute of Technology GmbH
CSV	Comma-separated values
DevOps	Development and Operations
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
JSON	JavaScript Object Notation
MBD	Multibody Dynamics
MBS	Multi-body simulation
ML	Machine Learning
ÖBB	Österreichische Bundesbahnen (Austrian Federal Railways)
PID	Proportional-Integral-Derivative
PNG	Portable Network Graphics
R4F	Rail for Future
RLT	Residual Life Time
SSP	System Structure and Parametrization
ViV	Virtual Vehicle Research GmbH
VTI	Vehicle Track Interaction

4 Problem Description / Objectives

4.1 Problem Description

After integrating railway simulation assets (model & data) into the R4F Platform by using specified interfaces and adapters (see Deliverable D1.1.4), it is imperative to ensure that the simulation outputs within the platform are consistent with the original results obtained from the default simulation software of these assets. Additionally, it is crucial to consider the outputs' relevance and applicability to the specific use cases of the assets. In some cases, it has been observed that the simulation results can show oscillating behavior compared to their original ones, which depends on the use case. Therefore, the asset simulations require further optimization by experimenting different simulation configurations (e.g., step size, solver) in order to reduce these oscillations.

Moreover, interpreting the simulation results generated within the platform poses a challenge for users. Therefore, it is essential to enhance the descriptiveness, precision, and visual clarity of these results. This can be achieved by utilizing open-source file formats (e.g., CSV, JSON) and generating visual representations through appropriate visualization tools, thereby providing the users with a more comprehensive and accessible understanding of the simulation outcomes.

4.2 Objectives

This deliverable aims to provide comprehensive and valuable insights into railway use cases associated with the platform's asset simulations by clearly and visually presenting the deployment results of these simulations. Besides, the optimized version of selected simulation results, derived from different simulation configurations, is also aimed to be presented in this report.

5 Significance for the overall Project

The railway use cases, shown and described in Deliverable D1.1.5, are pivotal to the Rail4Future Project. Thus, their implementation into the R4F Platform significantly contributes to the project by meeting the needs of the users of the platform including railway infrastructure managers and train operators. However, it is important to visually present the outputs of the use case implementation by deploying their simulation assets in the platform as well, because these outputs prove the success of the project. Leveraging DevOps practices, these outputs are automatically prepared and deployed on the platform, enabling the users to analyze, validate, and visualize them. This approach underscores the practicability and representativeness of the project.

6 Description

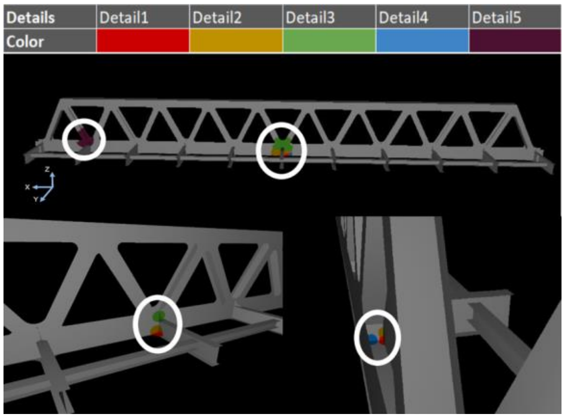
In this section, we present representative figures, tables and model pictures created and collected from the implementation of different railway use cases within the R4F Platform. These use cases encompass diverse railway assets, including simulation models utilized for automated integration and delivery testing in a demonstration version of the platform (see Deliverable D1.3.6 and Kugu et.al. [4]).

6.1 Residual Life Time Bridge Results

The RLT calculation of a railway steel bridge, provided from AIT, is demonstrated in the R4F Platform. As detailed in Deliverable D1.1.5 before, a Python script, including different calculation algorithms, is employed to perform the calculation with input parametrization and output generation. In this subsection, the generated outputs are residual lifetime (measured in years) and damage sum (measured in -/year), based on predefined detail points representing critical spots of the bridge. Initially, only one CSV table was generated from the code execution. For the Rail4Future project, the code was successfully packed into an FMU file, which is executed from another Python code. Then, the new Python code is extended with JSON file and PNG picture generation. The output JSON file is based on R4F standards and thus is more human-readable than the CSV table. The output PNG images, produced using the Matplotlib visualization library [1], include validation points, with one set depicting residual lifetime results and another illustrating damage sums.

Fig. 1 shows all the CSV tables, a small part of the JSON files, and validation points, resulting from the RLT calculation of a dummy bridge, Schellhammergasse bridge from Wiener Linien, ÖBB Mürzbrücke and ÖBB Eschenau bridge with the corresponding visual bridge images provided by AIT. The damage sum and lifetime outputs are simply written into different columns of the CSV tables with detail point names. Besides, these results are visually put into the JSON files with use case metadata such as id, description, file type, variable name, data type, unit and dependency information. As realized in the validation points of all the bridges, the result consistency between the FMI- and Python-based simulations in the deployment is succeeded in the platform. This means that all the bridges show a great behavior regarding to the RLT calculation process performed in the platform.

Dummy Bridge



[2]

Results in CSV Table

Detail	DamageSum [-/Year]	Lifetime [Years]
Detail1	0.000694194	1440.520213
Detail2	0.001287863	776.4801868
Detail3	0.09709452	10.29924247
Detail4	0.002814674	355.2809201
Detail5	9.48E-05	10549.62997

Results in JSON File


```
{
    "uc-parameters": [
        {
            "id": "Detail1_DamageSum",
            "value": "0.0006941936608479097"
        },
        {
            "id": "Detail1_LifeTime",
            "value": "1440.5202127293542"
        },
        {
            "id": "Detail2_DamageSum",
            "value": "0.0012878628675942476"
        },
        {
            "id": "Detail2_LifeTime",
            "value": "776.4801867981636"
        },
```

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```
    "uc-metadata": [
        {
            "id": "Restlebensdauerberechnung",
            "description": "...",
            "filetype": "OUTPUT",
            "output_parameters": [
                {
                    "id": "Detail1_DamageSum",
                    "name": "Detail1_DamageSum",
                    "type": "float",
                    "unit": "-/year",
                    "info": [
                        {
                            "dependency": "..."
                        }
                    ]
                },
```


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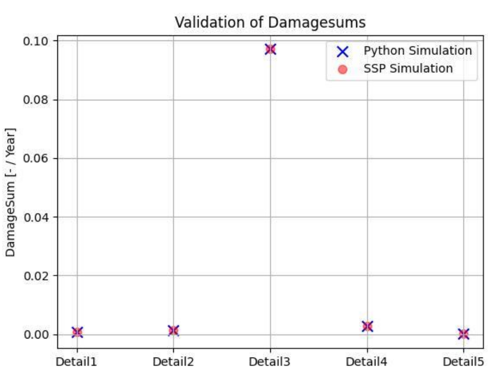
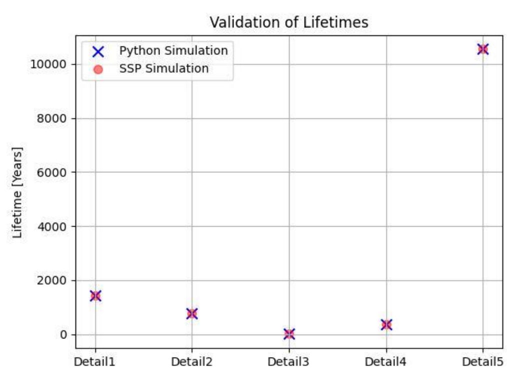
Validation Results (PNG Pictures)



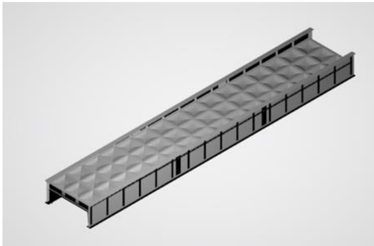
[2]

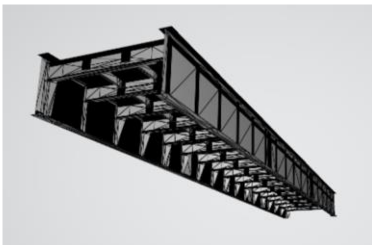


[2]

(1a)

Schellhammergasse Bridge from Wiener Linien	Results in CSV Table





Detail	DamageSum [-/Year]	Lifetime [Years]
HT-UG_Feldmitte	0	inf
HT-UG_Achse4-5	0	inf
QT-UG_Feldmitte	0	inf
QT-OG_Feldmitte	0	inf
Anschluss_Buckelblech_HT	0	inf

loadmodel_u6_2008-2017

Detail	DamageSum [-/Year]	Lifetime [Years]
HT-UG_Feldmitte	0.000318056	3144.096888
HT-UG_Achse4-5	0.000321756	3107.941818
QT-UG_Feldmitte	0.002526649	395.7810838
QT-OG_Feldmitte	0.000228436	4377.584727
Anschluss_Buckelblech_HT	7.55E-05	13242.55924

loadmodel_u6_2008-2017 - simplified

Results in JSON File


```
{
    "uc-parameters": [
        {
            "id": "Details",
            "value": "['HT-UG_Feldmitte', 'HT-UG_
        },
        {
            "id": "DamageSums",
            "value": "[0.0003180563563003, 0.0003
        },
        {
            "id": "Lifetimes",
            "value": "[3144.096887834291, 3107.94
        }
    ],
```

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```
    "uc-metadata": [
        {
            "id": "Restlebensdauerberechnung",
            "description": "...",
            "filetype": "OUTPUT",
            "output_parameters": [
                {
                    "id": "Details",
                    "name": "Details",
                    "type": "string",
                    "unit": "-",
                    "info": [
                        {
                            "dependency": "..."
                        }
                    ]
                },
```


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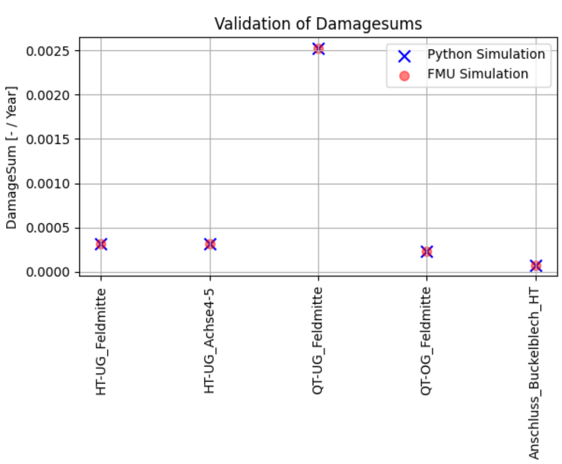
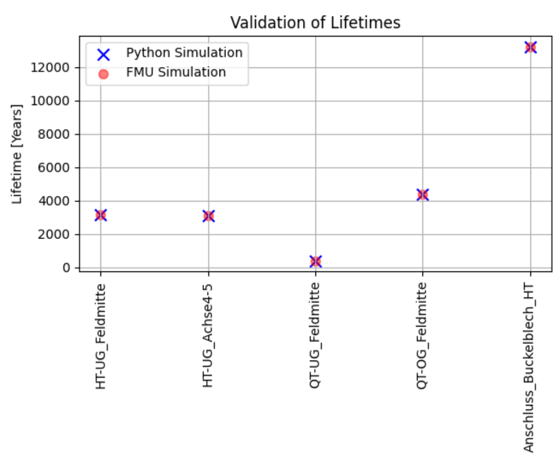
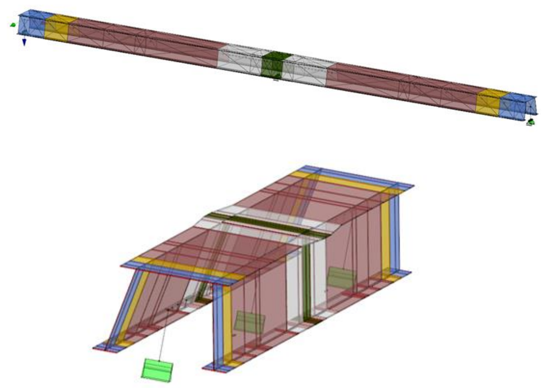
Validation Results (PNG Pictures)





(1b)

ÖBB Mürzbrücke



Results in CSV Table

Detail	DamageSum [-/Year]	Lifetime [Years]
Q5a-OG-R	0.008854583	112.93587
Q5a-UG-R	0.014138993	70.72639292
Q7a-OG-R	0.010438468	95.79950304
Q7a-UG-R	0.016401042	60.971734
Q7b-OG-R	0.010438468	95.79950304
Q7b-UG-R	0.016401042	60.971734
Q5b-OG-R	0.009964429	100.3569839
Q5b-UG-R	0.01566756	63.82614785

initial

Detail	DamageSum [-/Year]	Lifetime [Years]
Q5a-OG-R	0.009002157	111.0844876
Q5a-UG-R	0.011388141	87.81064387
Q7a-OG-R	0.010684233	93.59586225
Q7a-UG-R	0.013731846	72.82342296
Q7b-OG-R	0.010684233	93.59586225
Q7b-UG-R	0.013731846	72.82342296
Q5b-OG-R	0.00975591	102.5019758
Q5b-UG-R	0.014335049	69.75909393

calibrated

Results in JSON File

```
{
    "uc-parameters": [
        {
            "id": "Details",
            "value": "['Q5a-OG-R', 'Q5a-UG-R', 'Q7a
        },
        {
            "id": "DamageSums",
            "value": "[0.0088545826923192, 0.014138
        },
        {
            "id": "Lifetimes",
            "value": "[112.9358700176164, 70.726392
        }
    ],
```

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```
    "uc-metadata": [
        {
            "id": "Restlebensdauerberechnung",
            "description": "...",
            "filetype": "OUTPUT",
            "output_parameters": [
                {
                    "id": "Details",
                    "name": "Details",
                    "type": "string",
                    "unit": "-",
                    "info": [
                        {
                            "dependency": "..."
                        }
                    ]
                },
```

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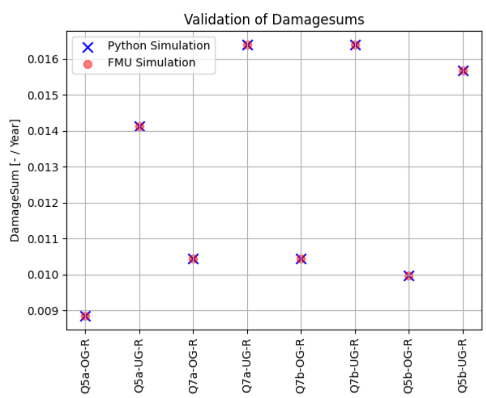
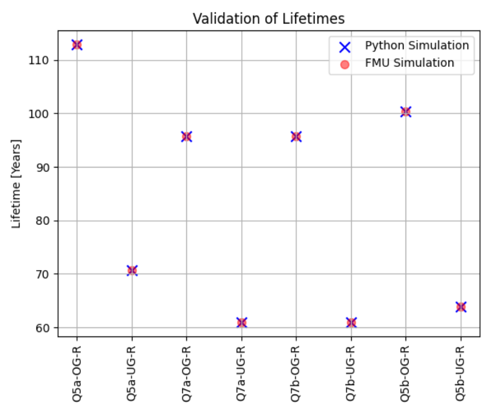
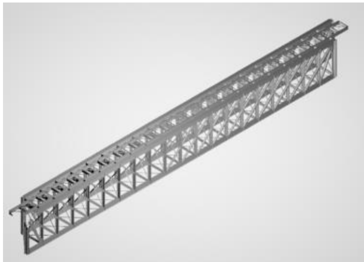
Validation Results (PNG Pictures)

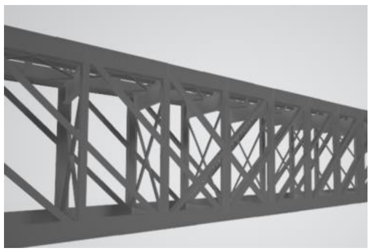




(1c)

ÖBB Eschenau Bridge





Results in JSON File

```
{
    "uc-parameters": [
        {
            "id": "Details",
            "value": "['s-1', 's-2', 's-3', 's-4
        },
        {
            "id": "DamageSums",
            "value": "[0.0, 0.0, 0.0, 0.0, 0.0, 
        },
        {
            "id": "Lifetimes",
            "value": "[inf, inf, inf, inf, inf, 
        }
    ],
```

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```
    "uc-metadata": [
        {
            "id": "Restlebensdauerberechnung",
            "description": "...",
            "filetype": "OUTPUT",
            "output_parameters": [
                {
                    "id": "Details",
                    "name": "Details",
                    "type": "string",
                    "unit": "-",
                    "info": [
                        {
                            "dependency": "..."
                        }
                    ]
                },
```

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Results in CSV Table

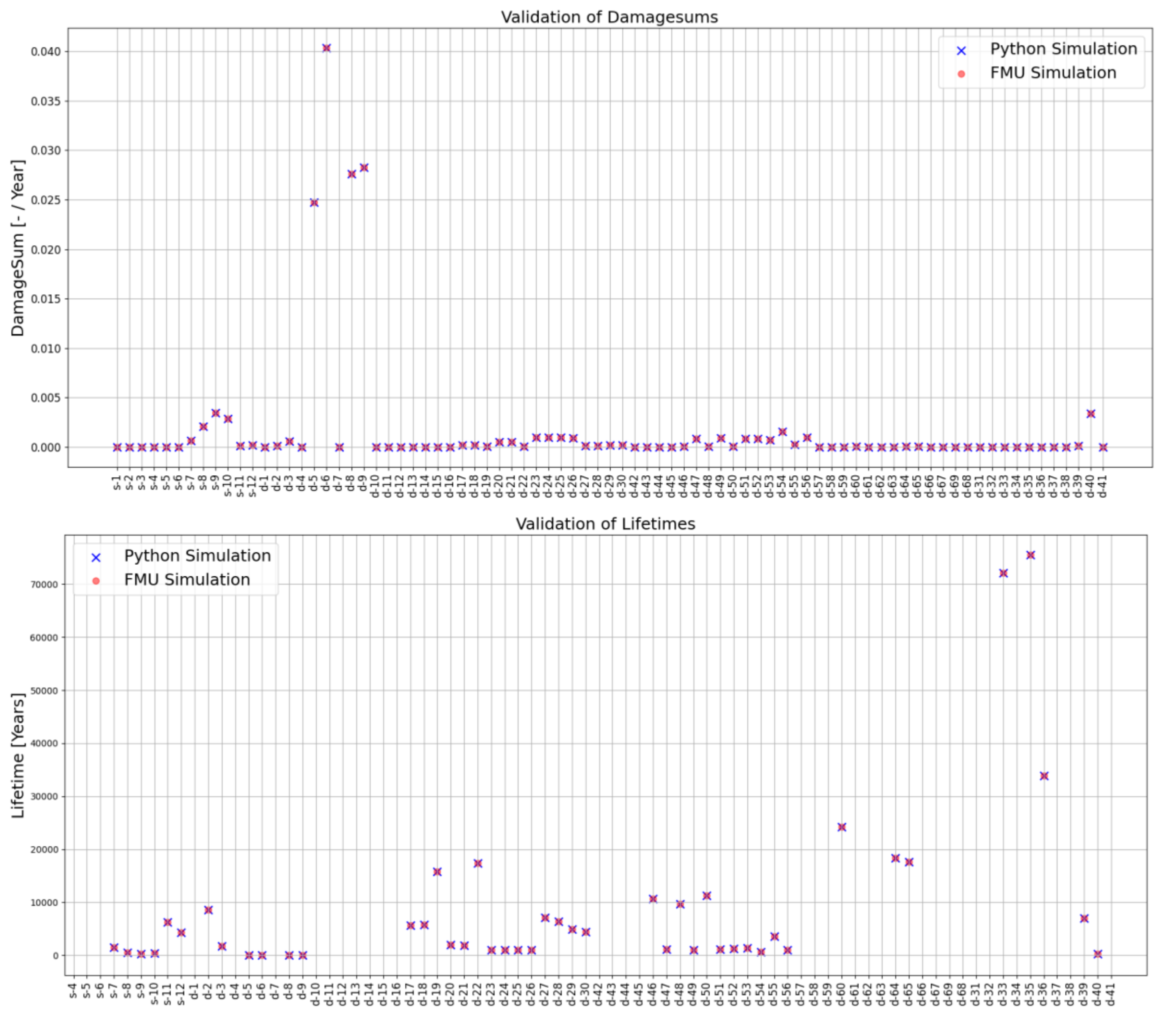
Detail	DamageSum [-/Year]	Lifetime [Years]
s-1	0	inf
s-2	0	inf
s-3	0	inf
s-4	0	inf
s-5	0	inf
s-6	0	inf
s-7	0.000689143	1451.077605
s-8	0.002111346	473.6314437
s-9	0.003470168	288.1705264
s-10	0.002864765	349.0687379
s-11	0.000158161	6322.659877
s-12	0.000233794	4277.264172
d-1	0	inf
d-2	0.000116568	8578.652466
d-3	0.000575414	1737.880025
d-4	0	inf
d-5	0.024710233	40.4690643
d-6	0.04032986	24.79552349
d-7	0	inf
d-8	0.027633371	36.18812932
d-9	0.028286583	35.35244937
d-10	0	inf
d-11	0	inf
d-12	0	inf
d-13	0	inf
d-14	0	inf
d-15	0	inf
d-16	0	inf
d-17	0.000175516	5697.498932
d-18	0.000172971	5781.321732
d-19	6.32E-05	15828.32334
d-20	0.000510994	1956.970929
d-21	0.000519456	1925.089522
d-22	5.77E-05	17325.34761
d-23	0.000996786	1003.224589
d-24	0.000978858	1021.598294
d-25	0.000960488	1041.137361
d-26	0.000944983	1058.220649
d-27	0.000140881	7098.181235
d-28	0.000155957	6412.026796
d-29	0.000205479	4866.67671
d-30	0.000226264	4419.616224
d-42	0	inf
d-43	0	inf
d-44	0	inf
d-45	0	inf
d-46	9.42E-05	10610.8003
d-47	0.000846854	1180.840752
d-48	0.000103238	9686.378111
d-49	0.0009448	1058.424923
d-50	8.86E-05	11284.45663
d-51	0.000839191	1191.623827
d-52	0.000834233	1198.706242
d-53	0.000754458	1325.45521
d-54	0.001578623	633.4636532
d-55	0.000275287	3632.574885
d-56	0.000967864	1033.203498
d-57	0	inf
d-58	0	inf
d-59	0	inf
d-60	4.13E-05	24221.2958
d-61	0	inf
d-62	0	inf
d-63	0	inf
d-64	5.44E-05	18387.94512
d-65	5.67E-05	17634.35786
d-66	0	inf
d-67	0	inf
d-69	0	inf
d-68	0	inf
d-31	0	inf
d-32	0	inf
d-33	1.39E-05	72081.44059
d-34	0	inf
d-35	1.32E-05	75552.29257
d-36	2.96E-05	33824.89486
d-37	0	inf
d-38	0	inf
d-39	0.000143187	6983.868546
d-40	0.003421944	292.2315314
d-41	0	inf

initial

Detail	DamageSum [-/Year]	Lifetime [Years]
s-1	0	inf
s-2	0	inf
s-3	3.81E-05	26274.75432
s-4	0	inf
s-5	0	inf
s-6	0	inf
s-7	0.003531385	283.1749938
s-8	0.007572685	132.0535667
s-9	0.017643572	56.67786459
s-10	7.07E-05	14139.27887
s-11	0.000234629	4262.046033
s-12	0.006471069	154.5339777
d-1	0	inf
d-2	0	inf
d-3	0	inf
d-4	0	inf
d-5	0.024914498	40.13727203
d-6	0.040717918	24.55921276
d-7	0	inf
d-8	0.027732656	36.0585728
d-9	0.028326466	35.30267429
d-10	0	inf
d-11	0	inf
d-12	0	inf
d-13	0	inf
d-14	0	inf
d-15	0	inf
d-16	0	inf
d-17	0.000195154	5124.153028
d-18	0.000194397	5144.122753
d-19	7.66E-05	13061.00673
d-20	0.000514787	1942.552372
d-21	0.000517459	1932.519689
d-22	5.96E-05	16780.92316
d-23	6.22E-05	16071.13829
d-24	0.000516463	1936.246104
d-25	0.001737575	575.5147794
d-26	0.003788518	263.95544
d-27	0.000486851	2054.015867
d-28	0.00011146	8971.861602
d-29	0	inf
d-30	0	inf
d-42	0	inf
d-43	0	inf
d-44	0	inf
d-45	0	inf
d-46	4.61E-05	21674.17171
d-47	0.000897265	1114.497683
d-48	4.91E-05	20386.67114
d-49	0.000947508	1055.399768
d-50	0.000135013	7406.718255
d-51	0.000820259	1219.127569
d-52	0.00091032	1098.514757
d-53	0.000743657	1344.70652
d-54	0.001685765	593.202569
d-55	7.84E-05	12761.68488
d-56	0.001065483	938.5411012
d-57	0	inf
d-58	0	inf
d-59	0	inf
d-60	3.27E-05	30551.48981
d-61	0	inf
d-62	0	inf
d-63	0	inf
d-64	6.38E-05	15669.32798
d-65	0.000103749	9638.646024
d-66	0	inf
d-67	0	inf
d-69	0	inf
d-68	0	inf
d-31	0	inf
d-32	0	inf
d-33	1.43E-05	70011.50002
d-34	0	inf
d-35	1.36E-05	73506.76702
d-36	2.97E-05	33660.30557
d-37	0	inf
d-38	0	inf
d-39	0.00094204	1061.525846
d-40	0.005613806	178.1322625
d-41	0	inf

calibrated

Validation Results (PNG Pictures)



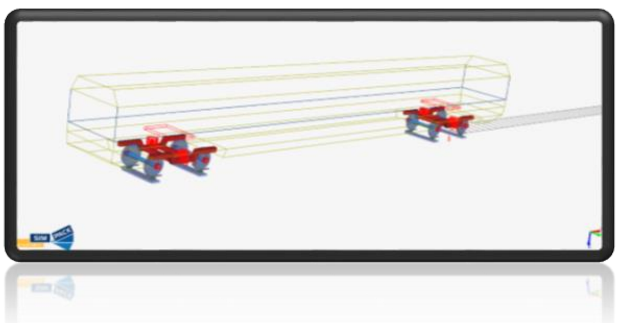
(1d)

Fig. 1: RLT Bridge results: (1a) Dummy Bridge; (1b) Schellhammergasse Bridge from Wiener Linien. (1c) ÖBB Mürzbrücke; (1d) ÖBB Eschenau Bridge;

6.2 Multi-body Simulation Railway Vehicle Model Results

As previously mentioned in Deliverable D1.1.5, we demonstrated the operation of a railway vehicle on straight and/or curved tracks using the Simpack MBS vehicle model. This model, based on the Manchester Benchmark [3], features two bogies and was provided by Virtual Vehicle. For this use case, vertical deflection of primary springs, implemented in the bogies, and actual track excitation (left & right) are observed as results. These observations are subsequently used for further lifetime calculations of the vehicle within the R4F Platform. Additionally, actual vehicle speed, time, and track position are included as outputs for validation purposes.

Fig. 2 shows a representative visual picture of the MBS vehicle, JSON output structure, based on the R4F standards, a small part of the generated CSV file, which can be used for data analysis purposes, and validation curves as a PNG image. This PNG image shows vertical deflection outputs (measured in meter) of one of the primary springs due to the track position (measured in meter), which are resulted from the FMI-based SSP and Simpack simulations for comparison purposes, and generated by using Matplotlib [1]. As simply realized in these curves, the FMI- and Simpack-based simulation results are highly consistent to each other, proving the successful deployment of the MBS model simulation in the platform.

<table>
<tr><th>Vehicle</th><th>CSV Table</th></tr>
<tr><td></td><td>

	A	B
1	TrackPosition_m	VerticalDeflection_m
2	0	-1.47E-07
3	0.0166667	2.28E-06
4	0.0333333	9.14E-06
5	0.05	2.00E-05
6	0.0666667	3.45E-05
7	0.0833333	5.17E-05
8	0.1	7.12E-05
9	0.116667	9.22E-05
10	0.133333	0.000114022
11	0.15	0.000135968
12	0.166667	0.000157428
13	0.183333	0.000177838

• • •
</td></tr>
</table>

JSON File	Validation Results (PNG Pictures)


```
{
    "uc-parameters": [
        {
            "id": "time",
            "value": "[0.01, 0.02, 0.
        },
        {
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        },
              ...
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        {
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            "description": "...",
            "filetype": "OUTPUT",
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                    "id": "time",
                    "name": "time",
                    "type": "float",
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                        {
                            "dependency": ""
                        }
                    ]
                },
              ...
```
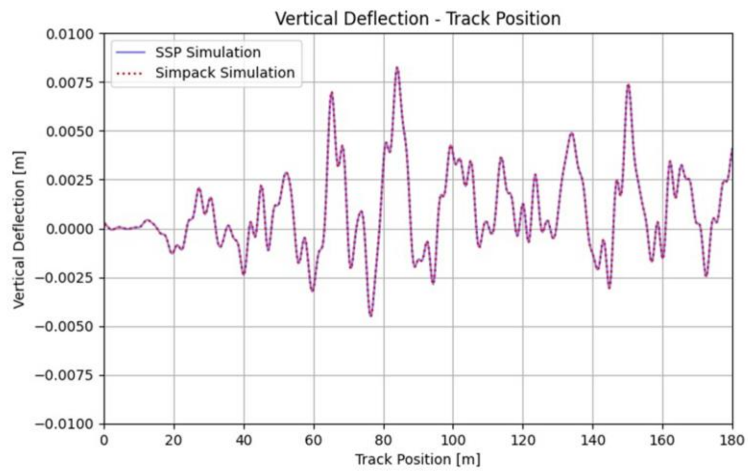




[2]

Fig. 2: MBS vehicle simulation results. [2]

6.3 Anti-Slip and Speed Traction Control Co-Simulation Results (MBS Railway Vehicle Model + PID-based Controller Model)

This use case helps to control the vehicle speed and anti-slip traction behavior of the MBS vehicle, consisting of two bogies and four wheelsets (two for each bogie). For this use case, we decided to observe the actual vehicle speed, wheel speed and actual slip resulted from the co-simulation in the R4F Platform.

In Fig. 3, a symbolic picture of the co-simulation model, CSV table part, JSON output structure and validation curves as PNG pictures are obtained. In fact, there are nine output ports implemented into the Simpack MBS model (see Deliverable D1.3.5). One belongs to the actual vehicle speed, the four to the wheel speed and the last four to the actual slip. Each of the four comes from each wheelset of the vehicle.

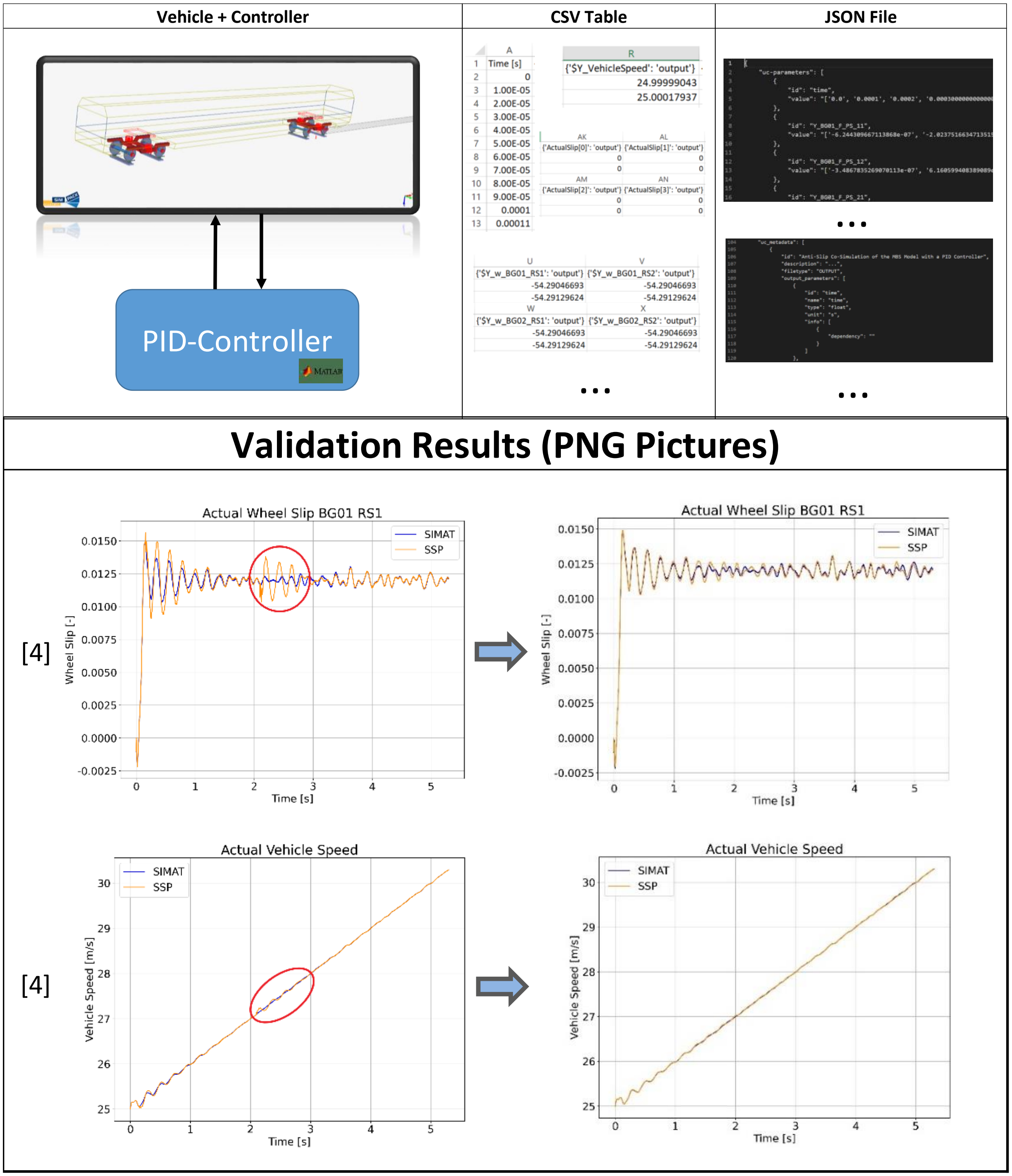


Fig. 3: Anti-Slip Co-Simulation results (MBS + PID). [4]

The validation curves shown in Fig. 3 are an optimized version of the previously obtained curves regarding to the trade-off between the simulation runtime and result quality. Either we reduce the simulation step size, change the simulation solver or both in order to decrease the oscillations unexpectedly occurring during the co-simulation process (marked with red circles in the validation results pictures in Fig. 3).

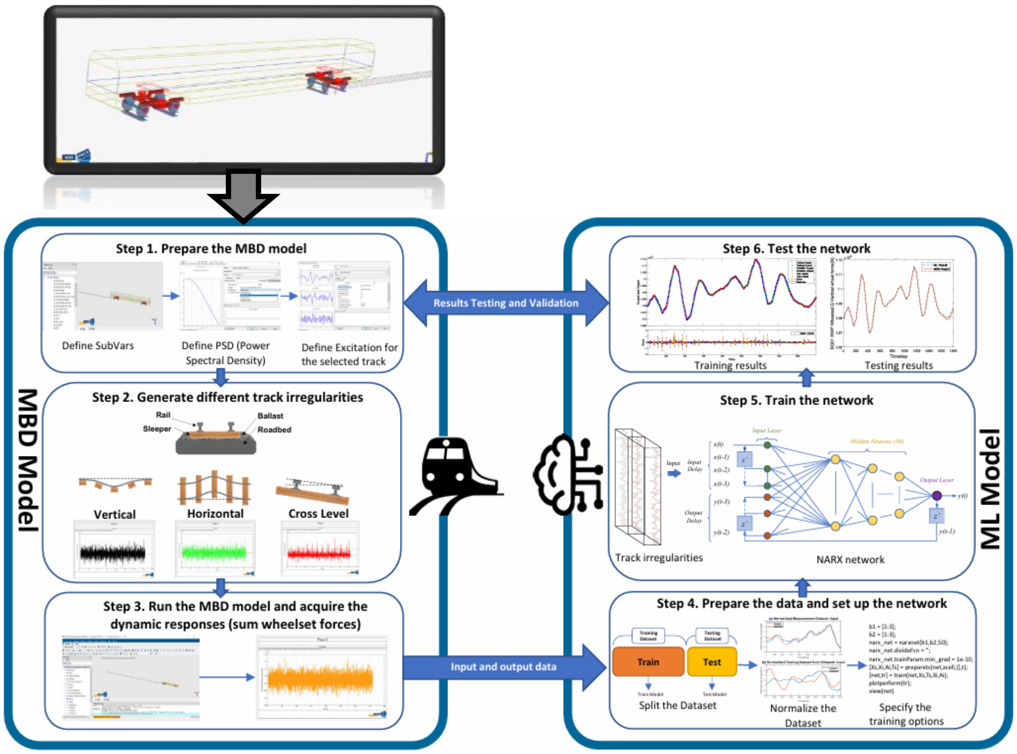
6.4 Machine Learning-based Surrogate Model Results (MBS Railway Vehicle Model)

In this case study, an ML-based surrogate model for MBS of railway vehicle-track dynamics is created, which can replace the railway vehicle-track simulation executed with the MBD Simulation commercial software Simpack. The well-built ML model can accurately and quickly predict the vehicle-track system's dynamic responses to different track irregularities. The calculation efficiency is also greatly improved. For a 5 km long railway, it only takes about 8 seconds for the surrogate model to finish the calculation, a value that is three orders lower than the time needed for the MBD simulation (30 minutes). In addition to computational complexity reduction, the surrogate model also demonstrates great potential in subsystem integration, as it can address the problem referring to different submodels' software and solver restrictions (see Zhou et.al. [5]).

In Fig. 4, the simulation results of the surrogate model are presented as a PNG image, including validation curves used for comparison between predicted and original results (Fig. 4b), and console output coming from the Jenkins pipeline server (Fig. 4c). Additionally, the figure includes a Simpack image of the MBS vehicle and a symbolic representation of the surrogate modelling methodology, as detailed in Zhou et.al. [5] (Fig. 4a). The validation curves display the actual wheelset forces (lateral direction, y) in Newton (N) as a function of track position in meters (m). The pipeline console output provides comprehensive insights into the surrogate model simulation. It includes some particular key data regarding to the simulation (e.g., time duration (training + simulation), simulation time step, number of parameters). After integrating the surrogate model into the platform, the validation results show relatively high consistency, which means that the simulation results of the original MBS simulation are well-predicted. This indicates the deployment success of the ML-based surrogate model in the platform.

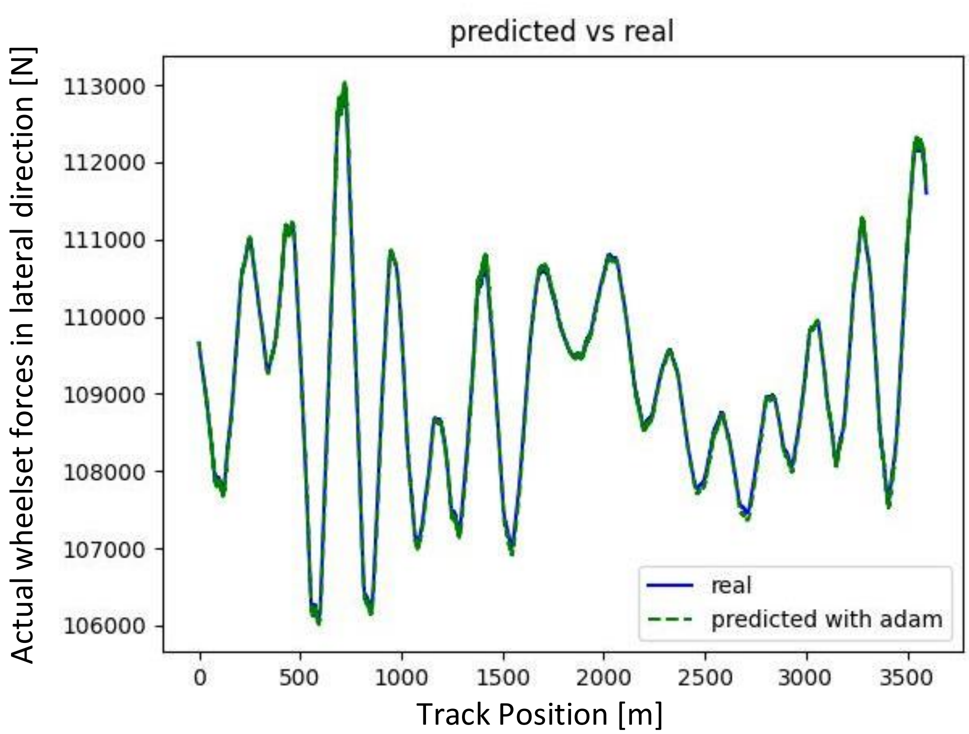
Vehicle + Machine Learning

[5]



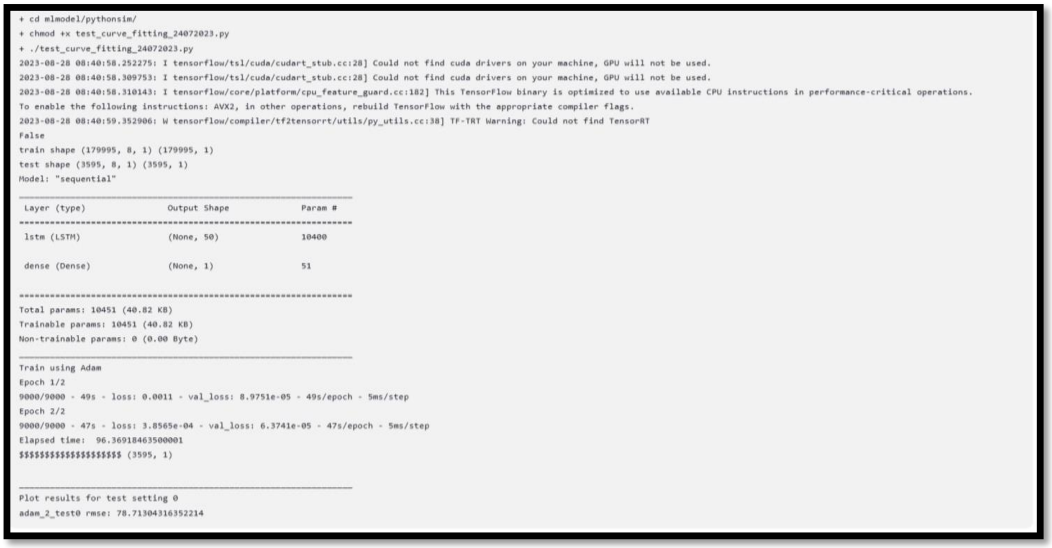
(a)

Validation Results (PNG Pictures)



(b)

Screenshot (Console Output)



```
+ cd mlmodel/pythonsim/
+ chmod +x test_curve_fitting_24072023.py
+ ./test_curve_fitting_24072023.py
2023-08-28 08:40:58.252275: I tensorflow/tsl/cuda/cudart_stub.cc:28] Could not find cuda drivers on your machine, GPU will not be used.
2023-08-28 08:40:58.309753: I tensorflow/tsl/cuda/cudart_stub.cc:28] Could not find cuda drivers on your machine, GPU will not be used.
2023-08-28 08:40:58.310143: I tensorflow/core/platform/cpu_feature_guard.cc:182] This TensorFlow binary is optimized to use available CPU instructions in performance-critical operations.
To enable the following instructions: AVX2, in other operations, rebuild TensorFlow with the appropriate compiler flags.
2023-08-28 08:40:59.352906: W tensorflow/compiler/tf2tensorrt/utils/py_utils.cc:38] TF-TRT Warning: Could not find TensorRT
False
train shape (179995, 8, 1) (179995, 1)
test shape (3595, 8, 1) (3595, 1)
Model: "sequential"
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 lstm (LSTM)                 (None, 50)                10400

 dense (Dense)               (None, 1)                 51

=================================================================
Total params: 10451 (40.82 KB)
Trainable params: 10451 (40.82 KB)
Non-trainable params: 0 (0.00 Byte)
_________________________________________________________________
Train using Adam
Epoch 1/2
9000/9000 - 49s - loss: 0.0011 - val_loss: 8.9751e-05 - 49s/epoch - 5ms/step
Epoch 2/2
9000/9000 - 47s - loss: 3.8565e-04 - val_loss: 6.3741e-05 - 47s/epoch - 5ms/step
Elapsed time:  96.36918463500001
$$$$$$$$$$$$$$$$$$$$ (3595, 1)

_________________________________________________________________
Plot results for test setting 0
adam_2_test0 rmse: 78.71304316352214
```

(c)

Fig. 4: ML-based surrogate model simulation results. [5]

6.5 VTI Use Case Results

The Vehicle Track Interaction Model, called VTI Model, is able to predict the evolution of the vertical track geometry [6]. This model was integrated successfully and deployed on the R4F platform and used to calculate the evolution of the vertical vehicle track geometry on the railway track from Graz to Bruck/Mur.

Therefore, the track was divided into sections with 200 m length where the standard deviation of the track geometry was investigated. Since the model is only supposed to give accurate predictions for sections that lack significant changes in track set-up, i.e. similar ballast, sleepers, fastenings, rails, rail pads and sleeper pads, it was first necessary to identify sections that include bridges or switches. These assets may introduce discontinuities, and the model results will be less accurate there. For this identification, a documentation provided by ÖBB was used.

Additionally, it is possible to derive a default vehicle mix from data delivered by ÖBB. This was an extract from their Artemis data base including data for a whole month in March 2022. This vehicle mix data can be adapted by users to fit their needs.

The results of the prediction by the VTI model can then be visualized in a Graphical User Interface.

A summary of the results is given in Fig. 5 for the track Bruck-Graz. It shows the standard deviation of the measured track geometry signal for different track sections with a length of 200 m. The red dots are the results for track sections where assets like bridges and switches can be found. As mentioned above, such assets often contain discontinuities in track parameters and, thus, the VTI Model is ill suited for predictions on these sections. Consequently, no simulations were performed there.

The blue dots show the measured standard deviation of the track geometry, while the respective error bars show the difference between measurement and simulation.

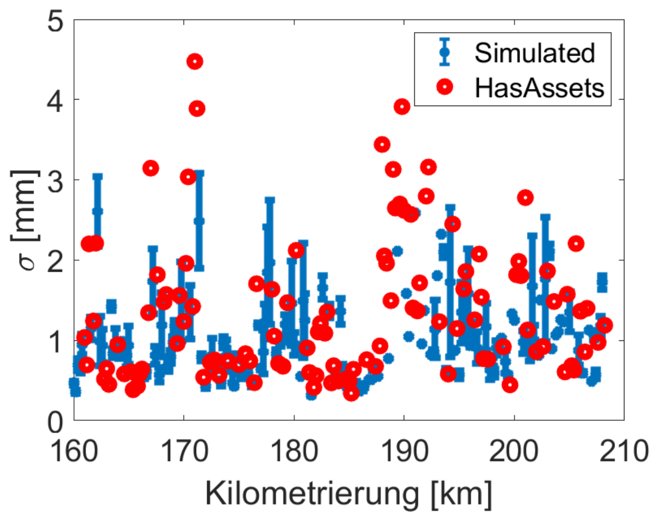


Fig. 5: Standard Deviation of the track geometry signal of the track Bruck-Graz for different sections of 200 m length. The red dots show the measurement results for sections that contain assets like bridges or switches while the blue dots show the results for sections with no assets. The blue error bars show the difference between measurement and simulations with the VTI Model.

One of the reasons for sometimes larger deviations is the difficulty to accurately consider maintenance actions. While a list with documented actions was provided by ÖBB, investigations of the data showed that multiple actions were not accurately documented: changes in track irregularities were seen in the data but no according actions were found. So, an automatic algorithm to detect such oddities in the data was created. While it worked well on many sections, it was prone to error: sometimes it failed to find such oddities (false negative) while sometimes it found oddities where a visual inspection of the data showed it was most likely just regular measurement noise (false positive).

An example of an oddity is shown in the right picture of Fig 6. There, a sudden drop in the standard deviation of the track geometry is visible at around 60 MGT. It is reasonable to assume that such a drop in the signal might have been caused by a maintenance action. However, there was no such action documented in the available data. Also, the oddity-detection algorithm was not able to find this automatically. It was only found due to manual inspection of the results. But once found, it was possible to explain the difference between the VTI Model and measurement since the VTI-Model cannot account for such sudden changes. A solution could be to set the parameters of the oddity-detection algorithm tighter, but this would only lead to many false positives – possible maintenance actions might be detected that were just naturally occurring fluctuations and noise in the data.

The left picture of Fig. 6 shows the results for the adjacent section. There, no maintenance action is visible in the data. However, this does not necessarily imply that there was no action performed, only that the result of such an action has no measurable influence on the track geometry signal. However, the predictions with the VTI Model are very well able to reproduce the measured data in this and similar cases.

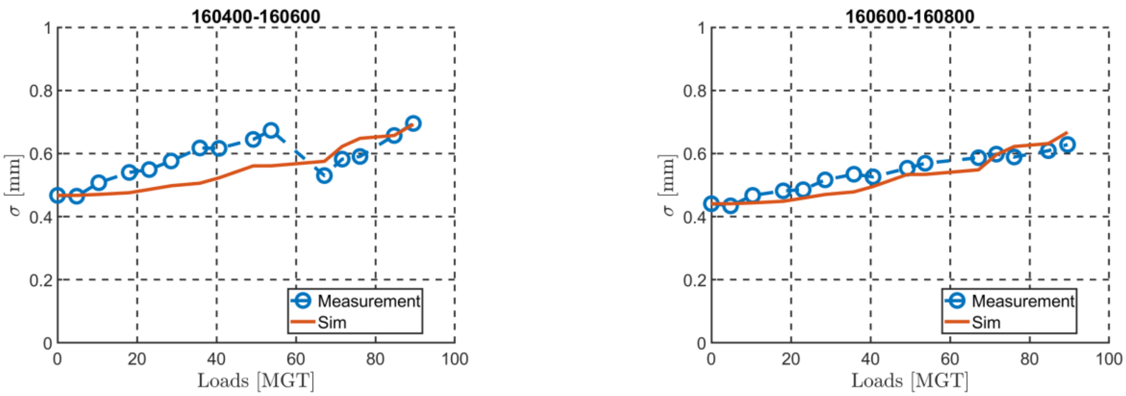


Fig. 6: Results for 2 different sections. In the left one, the algorithm did not consider the possible maintenance at around 60 MGT, while the right one shows good agreement.

Overall, the model is implemented on the platform and connected to the visualization platform. Tracks with assets like bridges or switches are excluded from the prediction. An oddity-detection algorithm was developed to account for maintenance actions that are not documented but found in the track geometry data. This oddity-detection algorithm works well for most sections but also delivers false positives and false negatives, which can only be detected by cumbersome and labor intensive manual inspections of the data. This causes issues in the prediction quality of the VTI Model, which otherwise gives reliable results and, thus, can be a good basis for a better planning of future maintenance.

7 Conclusion

This deliverable aims to present the insightful outputs of the Rail4Future project specifically focusing on simulation deployment results. These results derive from simulations of various assets of different railway subsystems. In some cases (e.g., anti-slip vehicle traction control), more than one simulation model is successfully interoperated with each other regarding to co-simulation. Besides, the visualization of all of these assets plays a massive role in representing several railway use cases, containing these assets, to the users of the R4F Platform. Consequently, this report includes visual representations of some simulation assets to provide readers with a clearer understanding of the use cases being applied to the platform. Detailed information on visualization can be found in D1.2.2 and D1.2.3.

Following the validation of simulation deployment results, all these assets will be applied to the prototype of the R4F Platform. Furthermore, the integration and delivery processes of these assets will be automated to save time and effort after manual testing of the asset simulations. More information about the automated integration and delivery methodology, and the prototypical R4F Platform is found in Deliverable D1.3.6 and Kugu et.al. [4].

8 References

[1] J. D. Hunter, "Matplotlib: A 2D Graphics Environment", Computing in Science & Engineering, vol. 9, no. 3, pp. 90-95, 2007. URL: https://doi.ieeecomputersociety.org/10.1109/MCSE.2007.55

[2] Kugu, O., Zhou, S., Nowak, R., Müller, G., Reiterer, S. H., Meierhofer, A., ... & Grafinger, M. (2023, December). An FMI-and SSP-based Model Integration Methodology for a Digital Twin Platform of a Holistic Railway Infrastructure System. In Modelica Conferences (pp. 717-726). URL: https://doi.org/10.3384/ecp204717

[3] Iwnick, S. (1998). Manchester benchmarks for rail vehicle simulation. Vehicle System Dynamics, 30(3-4), 295-313. URL: https://doi.org/10.1201/9780203736425

[4] Kugu, O., Zhou, S., Reiterer, S.H., Schwaiger, M., Wurth, L. and Grafinger, M. (2024). Pipeline-based Automated Integration and Delivery Testing of Simulation Assets with FMI/SSP in a Railway Digital Twin. American Modelica Conference 2024 (pp. 189-198). URL: https://doi.org/10.3384/ecp207189

[5] Zhou, S., Meierhofer, A., Kugu, O., Xia, Y., & Grafinger, M. (2023). A machine-learning-based surrogate modeling methodology for submodel integration in the holistic railway digital twin platform. Procedia CIRP, 119, 345-350. URL: https://doi.org/10.1016/j.procir.2023.02.141

[6] Kumar, N., Kossmann, K., Scheriau, S., Six, K. (2022). An efficient physical-based method for predicting the long-term evolution of vertical railway track geometries. Proc IMechE Part F: J Rail and Rapid Transit, Vol. 236(4), 447-465. URL: https://doi.org/10.1177/09544097211024803